NASA Technical Memorandum 100266

STAEBL/General Composites With Hygrothermal Effects (STAEBL/GENCOM)

Robert Rubenstein
Sverdrup Technology, Inc.
Lewis Research Center
Cleveland, Ohio

and

Christos C. Chamis
Lewis Research Center
Cleveland, Ohio

(NASA-TM-100266) STAEBL/GENERAL COMPOSITES WITH HYGROTHERMAL EFFECTS (STAEBL/GENCOM) (NASA) 14 p Avail: NTIS HC A03/MF A01 CSCL 11D
N88-13754
Unclas
G3/39 0114106

December 1987

NASA

STAEBL/GENERAL COMPOSITES WITH HYGROTHERMAL EFFECTS (STAEBL/GENCOM)

Robert Rubenstein
Sverdrup Technology, Inc.
Lewis Research Center
Cleveland, Ohio 44135

and

Christos C. Chamis
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

A computer code has been developed to perform structural optimization of turbine blades made from angle ply fiber composite laminates. Design variables available for optimization include geometric parameters such as blade thickness distribution and root chord, and composite material parameters such as ply angles and numbers of plies of each constituent material. Design constraints include resonance margins, forced response margins, maximum stress, and maximum ply combined stress. A general description of this code is given. Design optimization studies for typical blades are presented.

E-3896

INTRODUCTION

The design of composite turbine blades is a very complex problem involving a large number of design variables and constraints. Even after a blade cross-section is selected, the spanwise thickness distribution, root chord, ply thicknesses and angles, and blade cross-section stacking are all available to help meet performance constraints.

Structural optimization provides a formal, automated procedure for solving such complex design problems. Recent research at the NASA Lewis Research Center has led to the development of STAEBL (Structural Tailoring of Engine Blades) (fig. 1, refs. 1 and 2), which applied structural optimization techniques to turbine blade design. Capabilities have been added to STAEBL which make it a stand-alone portable computer code STAEBL/GENCOM for hygrothermal mechanical tailoring of composite turbine blades. The objective of this paper is to describe these capabilities.

STAEBL/GENCOM can be used to structurally tailor composite blades subjected to centrifugal, gas dynamic (pressure), thermal, and moisture loads. The thermal and mechanical properties are temperature and moisture dependent. Design variables include blade geometry variables such as the thickness distribution, root chord, and blade cross-section stacking. The blade is made of groups of plies consisting of up to seven different composite materials. Both the ply angles and the numbers of plies in each group are design variables. This allows optimization of the blade material. Constraints can be imposed on resonance margins, forced vibration response, tip displacements, and maximum root and ply combined stresses. Other program features include data transfer from finite element models and a stand-alone program version.

NOMENCLATURE

E Young's modulus

E_O Young's modulus at reference temperature and zero moisture

M current moisture percentage by weight

T current temperature

T_{GD} dry glass transition temperature

T_{GW} wet glass transition temperature

T_O reference temperature

α thermal expansion coefficient

α_O thermal expansion coefficient at reference temperature and zero moisture

THE ORIGINAL STAEBL PROGRAM

The original version of STAEBL was developed by Pratt & Whitney under contract to NASA Lewis. It combines the optimization program COPES/CONMIN with a special blade geometry preprocessor and finite element analysis program as described in reference 1. The optimization algorithm implemented by COPES/CONMIN is the method of feasible directions. Typical design variables include blade thickness distribution and root chord. The blade profiles are changed only by similarity transformations and stretching along the chord axis. Typical constrained quantities include resonance margins on the Campbell diagram, root stress, and thickness to chord ratios. The blade is loaded by centrifugal stresses only. In order to apply this program to composite blade design, it was modified and augmented as described in the following sections.

HYGROTHERMAL STRESS ANALYSIS

Because STAEBL/GENCOM models the blade with triangular plate elements, the blade temperature and moisture distributions are assumed to be given at each grid point by a mean value, a through-thickness gradient, and because of different material properties through the thickness, by a through-thickness quadratic term. Two types of temperature and moisture input are allowed: the nodal quantities can be specified at each point, or they can be computed from known surface distributions using quadratic curvefits with coefficients specified by the user. Equivalent nodal thermal and hygral forces are computed in the usual way and are added to the nodal centrifugal forces. The stress recovery procedure compensates for free thermal and hygral expansion. Boundary conditions allow free expansion along the blade root.

TEMPERATURE DEPENDENT MECHANICAL AND THERMAL PROPERTIES

The new program version permits the elastic moduli to vary with element temperature T according to the formula

$$E = E_o\left[\left(\frac{T_{GD} - T}{T_{GD} - T_o}\right)\right]^{1/2}$$

Since E_o, T_{GD}, and T_o are all user input, suitable choices for these constants should given enough accuracy for most applications. Similarly, the thermal expansion coefficient varies with temperature according to

$$\alpha = \alpha_o\left[\left(\frac{T_{GD} - T}{T_{GD} - T_o}\right)\right]^{-1/2}$$

Equivalent properties for composite materials are computed using lamination theory (ref. 3).

TEMPERATURE AND MOISTURE-DEPENDENT MECHANICAL AND THERMAL PROPERTIES

The elastic constants, and the thermal and moisture expansion coefficients are assumed to vary with moisture and temperature according to the general formula (ref. 4).

$$P(T,M) = P(T)\left[\left(\frac{T_{GW} - T}{T_{GD} - T_o}\right)\right]^{EXP}$$

where

$T_{GW} = T_{GD}(0.005M^2 - 0.1M + 1)$

and

T = current temperature

T_o = reference temperature (input)

EXP = a characteristic exponent (input)

T_{GD} = a characteristic temperature (input)

M = current moisture percent by weight

COMPOSITE BLADE PREPROCESSING

STAEBL/GENCOM can analyze and optimize a composite blade containing groups of plies consisting of up to seven different materials. The user supplies the ply thicknesses, ply angles, and ply thermomechanical properties. The number of plies in each group, and the ply angles are possible design variables for optimization. The program assumes that the ply layup is symmetric, and that the ply angles in each group have the same magnitude and alternating signs. The program can also handle blades made from hybrid composites as depicted in figure 2.

The number of plies in each group is adjusted so that the airfoil design thickness is never exceeded. The outer ply group is always present. If the design thickness is sufficient, groups of plies of constant thickness of the remaining materials are added. The number of inner plies is variable, and is adjusted so that the design thickness is achieved.

STATIC PRESSURE LOADS

STAEBL/GENCOM allows user input of resultant gas dynamic pressures on each element. The pressures are replaced by statically equivalent nodal forces. These forces are added to the centrifugal and thermal loads. Thus, the total static load is the resultant of centrifugal, thermal, moisture, and pressure loads.

FATIGUE LIFE ANALYSIS

The original STAEBL program analyzed fatigue life using the Goodman diagram. It had a hard-coded forcing function appropriate for only one specific blade. In STAEBL/GENCOM, the forcing function is a multiple of the static pressure distribution at the blade natural frequencies which cause the greatest fatigue stress.

The required multiple of the static pressure, and the static and dynamic limits on the Goodman diagram are all user input. STAEBL/GENCOM models thermal effects on fatigue life by automatically making the static and dynamic limits vary with temperature like the elastic constants.

TIP DISPLACEMENT CONSTRAINTS

Excessive untwist and uncamber under load could cause significant engine power losses. Composite blade design must therefore consider tip displacements. STAEBL/GENCOM allows untwist, uncamber, and tip extension to be selected as constraints on the optimal design.

IMPROVED EXECUTION TIME AND STAND-ALONE ANALYSIS CAPABILITIES

The STAEBL program requires an aerodynamic blade geometry description commonly used by blade designers. Each cross-section is modeled by densely spaced points which surround the cross-section. STAEBL converts this description into a finite element model based on triangular plate elements. The design perturbations generated by the feasible directions method are applied to the aerodynamic blade description. Therefore, each trial design must invoke a preprocessor to convert the aerodynamic description to a finite element description. STAEBL/GENCOM includes an option which allows direct input of a finite element model. Design perturbations are carried out directly on this model. Approximately 12 percent time savings can be obtained using this version.

The original program version invoked IMSL library routines to perform the matrix operations required by finite element analysis. The new version includes replacements for these library routines. The program can execute independently of the IMSL library and can, therefore, be used at installations where this library is not available. However, user optional calls to IMSL library are available.

OFFSET DESIGN VARIABLES

Blade cross-section stacking is defined by the curve formed by the centers of gravity of the spanwise blade cross-sections. The deviation of this curve from a straight line perpendicular to the engine axis is called "offset."

Offset has been made available as a design variable in STAEBL/GENCOM. Offset is determined by variables A, B, C, D, E, and F through the equations

$$X = AZ + BZ^2 + CZ^3$$

$$Y = DZ + EZ^2 + FZ^3$$

where Z is a spanwise variable, X is transverse, and Y is chordwise.

Offset is used by blade designers to balance the centrifugal and aerodynamic pressure loads on a blade. The goal of this procedure is to reduce the static stress.

DEMONSTRATION CASES

STAEBL/GENCOM was applied to optimize the design of a sample composite blade. A propfan blade geometry was assumed, but the blade was assumed to be entirely graphite-epoxy. The composite layup consisted of an outer group of plies, two middle groups of plies, and a core group of plies. The blade geometry was that of an existing blade, and is already nearly optimal.

In a first study, the blade was subject to centrifugal loads only. The minimum weight design was sought subject to representative design requirements. The initial design violated the constraint on ply combined stress in the outer plies at the root. The initial and final blade geometries are compared graphically in figure 3. STAEBL/GENCOM also recommended a slight reorientation of the ply angle in the outer layer. Comparisons between the constrained variables in the initial and optimized designs appear in figure 4.

In a second study, the same blade was analyzed subject to centrifugal and to thermal and moisture loads believed to be representative for such blades. The optimized design weighs about 5 percent more than the design optimized for centrifugal loads alone. The initial and final designs are compared in figure 5, and the constrained variables are compared in figure 6.

The separate effects of temperature and moisture in optimal design are shown in tables I and II. These tables compare designs optimized under centrifugal loads alone, centrifugal and thermal loads, centrifugal and moisture loads, and centrifugal, thermal, and moisture loads. In this case, the thermal loads clearly have the dominant effect on the weight of the optimal design.

In order to expedite the optimization procedure, which requires analysis of a large number of trial designs, STAEBL/GENCOM uses a coarse-meshed finite element blade model. When STAEBL/GENCOM is applied in a design environment, the approximate analysis should be verified by a refined analysis. This is illustrated in the right half of figure 1.

CONCLUSIONS

The structural tailoring code STAEBL/GENCOM provides an effective and practical approach to design composite blade subject to complex mechanical and environmental loads. The large number of design variables associated with composite blade design, which include both blade geometry description variables and composite material design variables, can easily be incorporated into optimization algorithms. Both thermal and moisture effects can be modeled as part of the tailoring process. The demonstration cases demonstrate the versatility and computational capability of STAEBL/GENCOM.

REFERENCES

1. Brown, K.W.; Pratt, T.K.; and Chamis, C.C.: Structural Tailoring of Engine Blades (STAEBL). 24th AIAA Structures, Structural Dynamics and Materials Conference, Part 1, AIAA, 1983, pp. 79-88.

2. Brown, K.W.; Hirschbein, M.S.; and Chamis, C.C.: Finite Element Engine Blade Structural Optimization. 26th AIAA Structures, Structural Dynamics and Materials Conference, Part 1, AIAA, 1985, pp. 793-803.

3. Chamis, C.C.; and Smith, G.T.: Resin Selection Criteria for "Tough" Composite Structures. AIAA J., vol. 23, no. 6, June 1985, pp. 902-911.

4. Chamis, C.C.; and Smith, G.T.: Environmental and High Strain Rate Effects on Composites for Engine Applications. AIAA J., vol. 22, no. 1, Jan. 1984, pp. 128-134.

TABLE I. - COMPARISON BETWEEN DESIGNS OPTIMIZED FOR DIFFERENT LOADING CONDITIONS: DESIGN VARIABLES AND OBJECTIVE FUNCTION

Percent span	Centrifugal only		Centrifugal and thermal loads		Centrifugal and moisture loads		Centrifugal, thermal, and moisture loads	
	Thickness	Chord	Thickness	Chord	Thickness	Chord	Thickness	Chord
0	1.77	11.80	1.80	11.98	1.77	11.80	1.80	11.98
40	.65	13.08	.70	13.28	.65	13.09	.70	13.28
80	.27	7.88	.27	8.00	.27	7.88	.27	7.99
100	.12	3.44	.12	3.49	.12	3.44	.12	3.49
Blade weight	16.73		17.44		16.73		17.45	

Location	Ply design for all load conditions	
	Ply thickness	Ply angle, deg
Outer	0.09	45
Layer 1	.09	0
Layer 2	.10	45
Core	----	0

TABLE II. - COMPARISON BETWEEN DESIGNS OPTIMIZED FOR DIFFERENT LOADING CONDITIONS: RESPONSE VARIABLES

	Centrifugal loads only	Centrifugal and thermal loads	Centrifugal and moisture loads	Centrifugal, thermal, and moisture loads
Natural frequency, Hz				
Mode 1	59.7	58.8	59.7	58.8
Mode 2	238.3	229.2	238.3	229.1
Mode 3	413.0	396.5	412.9	396.4
Ply combined stress margin of safety				
Outer	0.44	0.45	0.44	0.45
Layer 1	.74	.70	.74	.70
Layer 2	.28	.20	.28	.21
Core	.66	.63	.66	.63
Tip displacements				
Untwist, deg	0.15	0.08	0.15	0.08
Uncamber, deg	.03	.13	.03	.13
Extension, in.	.03	.05	.03	.05

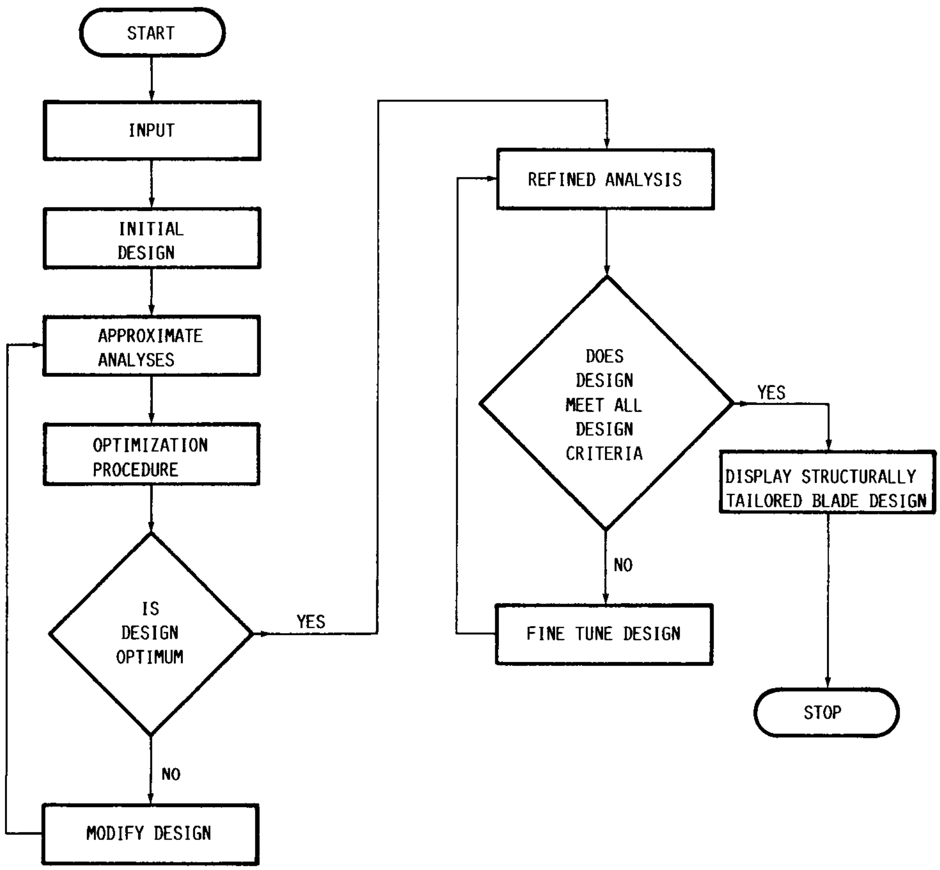

FIGURE 1. - STRUCTURAL RAILORING OF ENGINE BLADES (STAEBEL).

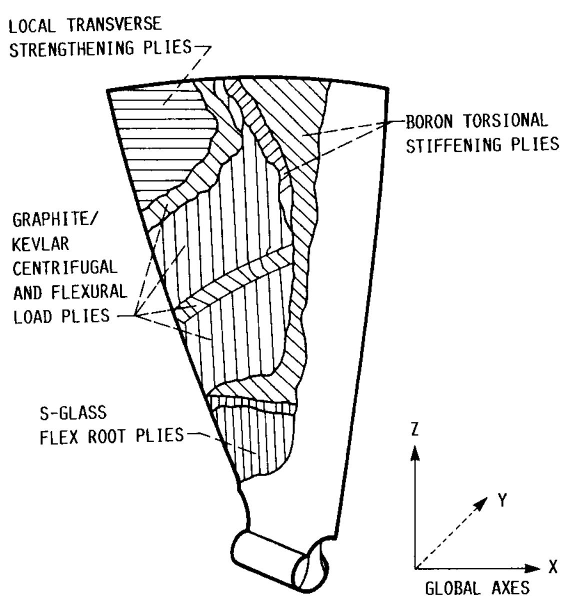

FIGURE 2. - COMPOSITE BLADE.

COMPOSITE MATERIAL PARAMETERS				
	INITIAL DESIGN		OPTIMIZED DESIGN	
	PLY THICKNESS, IN.	PLY ANGLE	PLY THICKNESS, IN.	PLY ANGLE
OUTER LAYER	.10	45.	.10	45.
LAYER 1	.10	0.	.10	0.
LAYER 2	.10	45.	.10	45.
CORE		0.		0.
	BLADE WEIGHT			
	17.88 LB		16.73 LB	

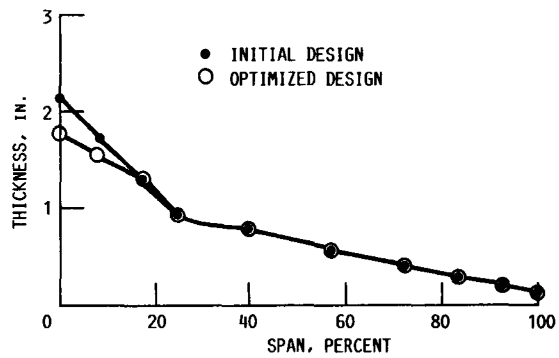

FIGURE 3. - COMPARISON BETWEEN INITIAL AND OPTIMIZED DESIGNS, CENTRIFUGAL LOADS ONLY.

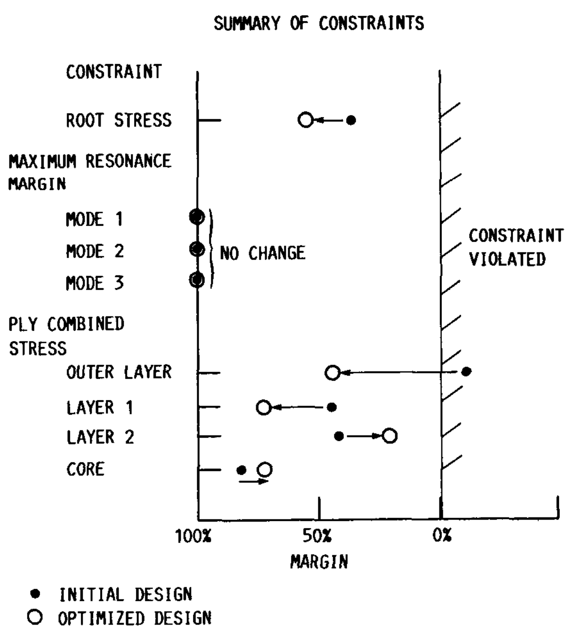

FIGURE 4. - COMPARISON BETWEEN INITIAL AND OPTIMIZED DESIGNS, CENTRIFUGAL LOADS ONLY.

COMPOSITE MATERIAL PARAMETERS				
	INITIAL DESIGN		OPTIMIZED DESIGN	
	PLY THICKNESS, IN.	PLY ANGLE	PLY THICKNESS, IN.	PLY ANGLE
OUTER LAYER	.10	45.	.09	45.
LAYER 1	.10	0.	.09	0.
LAYER 2	.10	45.	.10	45.
CORE		0.		0.
	BLADE WEIGHT			
	17.88 LB		17.45 LB	

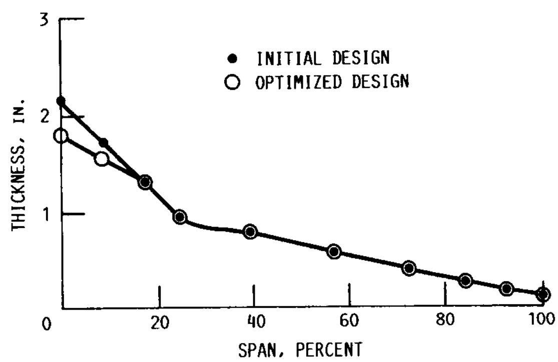

FIGURE 5. - COMPARISON BETWEEN INITIAL AND OPTIMIZED DESIGNS CENTRIFUGAL, THERMAL, AND MOISTURE LOADS.

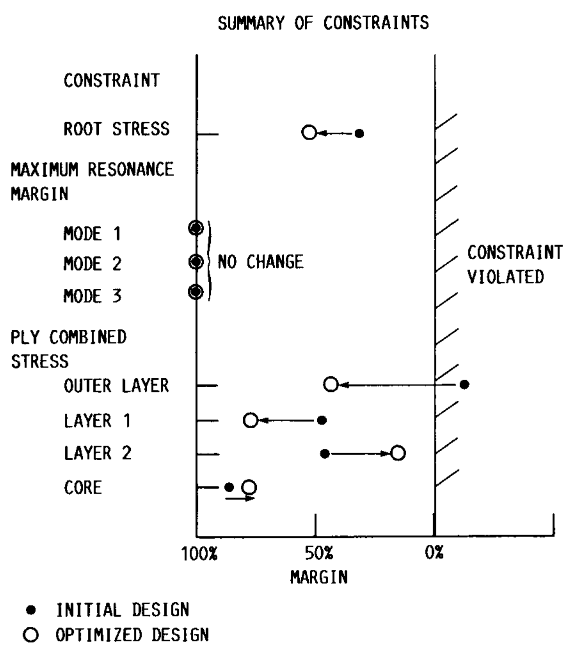

FIGURE 6. - COMPARISON BETWEEN INITIAL AND OPTIMIZED DESIGNS, THERMAL, MOISTURE, AND CENTRIFUGAL LOADS.

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA TM-100266	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle STAEBL/General Composites With Hygrothermal Effects (STAEBL/GENCOM)		5. Report Date December 1987
		6. Performing Organization Code
7. Author(s) Robert Rubenstein and Christos C. Chamis		8. Performing Organization Report No. E-3896
		10. Work Unit No. 505-45-58
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001		14. Sponsoring Agency Code

15. Supplementary Notes

Robert Rubenstein, Sverdrup Technology, Inc., Lewis Research Center, Cleveland, Ohio 44135; Christos C. Chamis, NASA Lewis Research Center.

16. Abstract

A computer code has been developed to perform structural optimization of turbine blades made from angle ply fiber composite laminates. Design variables available for optimization include geometric parameters such as blade thickness distribution and root chord, and composite material parameters such as ply angles and numbers of plies of each constituent material. Design constraints include resonance margins, forced response margins, maximum stress, and maximum ply combined stress. A general description of this code is given. Design optimization studies for typical blades are presented.

17. Key Words (Suggested by Author(s)) Optimization; Design constraints; Campbell diagram; Goodman diagram; Resonance margin; Turbopump blade	18. Distribution Statement Unclassified - Unlimited Subject Category 39

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	11	A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161